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DYNAMIC FRACTURE TOUGHNESS PARAMETERS FOR
HY-80 AND HY-130 STEELS AND THEIR WELDMENTS

by

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Lower bound dynamic fracture toughness parameters for HY-80 and HY-130 steel and their weld metals are identified. Specific values of the parameters K_{Id} and K_{Im} obtained from direct measurements are reported together with estimates inferred from the large body of Charpy energy, nil ductility transition temperature and dynamic tear energy measurements. The emphasis is on reasonable lower bound values at 30 F, the lowest anticipated service temperature, for use in elastodynamic analyses of crack growth initiation, propagation, and arrest in ship structures. For these conditions, it has been found that the ratio K_{Id}/σ_Y is ——

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ABSTRACT

Lower bound dynamic fracture toughness parameters for HY-80 and HY-130 steel and their weld metals are identified. Specific values of the parameters K_{Id} and K_{Im} obtained from direct measurements are reported together with estimates inferred from the large body of Charpy energy, nil ductility transition temperature and dynamic tear energy measurements. The emphasis is on resonable lower bound values at 30° F, the lowest anticipated service temperature, for use in elastodynamic analyses of crack growth initiation, propagation, and arrest in ship structures. For these conditions, it has been found that the ratio K_{Id}/σ_Y is approximately equal to 2 $inches^{1/2}$ for HY-80 steel. For HY-130 steel and the HY-80 and Hy-130 weld metals under these same conditions, K_{Id}/σ_Y is approximately 1 $inch^{1/2}$. Consequently, HY-80 plate appears to be substantially more resistant to fracture under dynamic loading than are the other three grades examined.

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HY-80 AND HY-130 STEELS AND THEIR WELDMENTS

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INTRODUCTION

Applications of dynamic fracture mechanics to treat crack growth
initiation, unstable propagation, and arrest can now only be made in conditions
where an elastodynamic analysis is applicable. Successful analyses have al-
ready been made of impact experiments [1, 2], nuclear pressure vessels under
thermal shock conditions [3, 4] and gas transmission pipelines [5, 6]. How-
ever, the ability to perform an elastodynamic analysis alone is not enough
to obtain results of practical interest. Values of the materials's resistance
to crack propagation—the dynamic fracture toughness parameters—must also be
available. Unfortunately, for the tough ductile materials used in most
engineering structures, these values are not easy to obtain.

The work reported here is part of a larger effort aimed at providing
a basis for crack propagation analyses in flawed ship hulls subjected to shock
loading. Previous work in this program has shown that elastodynamically de-
rived stress intensity factors can be used to predict crack growth initiation
and propagation under impact loads [1]. Hence, while further development of
the approach is still needed—e.g., to take direct account of crack tip plas-
ticity—it is possible to provide preliminary estimates to evaluate ship hull
performance by coupling these analyses with the material toughness parameters
for the HY-grade steels. This report takes a first step toward the acquisition
of suitable values for such analyses by means of a literature survey of the
fracture properties of HY-80 and HY-130 and their weld metals.

BACKGROUND DISCUSSION

The analysis of crack growth initiation from a preexisting crack in a structure and its subsequent rapid unstable propagation and arrest can now only be effectively treated using elastodynamically determined stress intensity factors. The stress intensity factor arises in the computed stress field attending a crack tip. In general, it depends on time, the crack propagation speed, the crack length, the external geometry of the cracked body, and the applied loads. For a crack propagating in opening made conditions under fixed external loading, an elastodynamic solution can generally be made, albeit numerically, to determine the stress intensity factor in the form $K_I = K_I (t, \dot{a})$ where $\dot{a}$ denotes the instantaneous crack speed and t is time.

The criteria governing crack growth initiation and propagation can be expressed in terms of K_I and experimentally determined critical values that are taken as material properties. First, for the onset of growth for a rapidly loaded stationary crack

$$K_I (t, o) = K_{Id} (\dot{K}) \tag{1}$$

where $\dot{\sigma}$ denotes the time rate of change of the applied loading through the consequent variation in the stress intensity factor. Like K_{Ic}, the conventional fracture toughness, K_{Id} will also be a function of temperature. Of course, for quasi-static loading, K_{Id} is identical with K_{Ic}.

The deformation state ahead of a propagating crack is generally different from that of a stationary crack. Consequently, the fracture property associated with a moving crack will differ from one that is not. The criterion for a rapidly propagating crack takes the form

$$K_I (t, \dot{a}) = K_{ID} (\dot{a}) \tag{2}$$

where K_{ID}, in addition to being a function of temperature, is assigned a crack speed-dependence to take account of the rate dependence. It is of some importance to recognize that the entire $K_{ID} = K_{ID} (\dot{a})$ need not be known to perform

an effective calculation. The minimum value of this function at a given temperature - conventionally designated as K_{Im} - will suffice in many instances.

Equations (1) and (2), respectively, give quantitative criteria for crack growth initiation and subsequent unstable propagation. A third such relation is sometimes used for crack arrest which involves a statically computed value of K_I and an "arrest toughness" parameter K_{Ia}. However, while this approach can be useful as an approximation in some conditions, it is not logically correct. Within the context of an elastodynamic approach, crack arrest will occur when Equation (2) can no longer be satisfied. That is, a propagating crack will arrest at a time t_a when $K_I > K_{Im}$ for all $t > t_a$. While it is true that under some conditions K_{Ia} is about equal to K_{Im}, it does not follow that such an approach is widely applicable. Rather, crack arrest is properly viewed as the termination point of a general dynamic crack propagation event for which the relevant fracture property is K_{Im}.

Methods of measuring K_{Id} ($\dot{K}$), K_{ID} ($\dot{a}$), and K_{Im} have been devised and efforts to produce ASTM standards for these tests are underway[9]. However, very few measurements of this type have so far been performed on the HY-80, HY-100 and HY-130 grades of steel and their weldments. The main reason for this is that the high toughness values displayed by these materials at service temperatures call for prohibitively large LEFM-type test pieces*.

The bulk of the evaluations performed by the NRL (Naval Research Laboratory) and by industry rely on less costly measures of toughness: CVN-(Charpy V-notch) energy, NDT-(Nil Ductility Transition) temperature and DTE (Dynamic Tear Energy). These relative measures of toughness can be used to obtain more-or-less approximate estimates of K_{IC}, K_{Id}, and K_{Im} by way of a number of empirical correlations identified in Table 1 and Appendix A. Of these, the NRL DTE-K_{IC} correlation, (Correlation No. 1 in Table 1) is probably the most important because NRL relies on it to establish material toughness requirements.

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*The logical extension of the ASTM E-399 fracture toughness test standard size requirements to dynamic loading would call for the crack length and thickness requirement a, B $\geq$ 2.5 $(K_{Id}/\sigma_Y d)^2$, where σ_{Yd} is the dynamic yield stress. Accordingly, a test piece about 20 in. x 20 in. x 10 in. is needed to measure shelf level toughness values, i.e., $K_{Id} \simeq$ 200 ksi $\sqrt{in}$ of HY-80 steel ($\sigma_{Yd} \simeq$ 100 ksi $\sqrt{in}$).

TABLE 1. SUMMARY OF TOUGHNESS CORRELATIONS

No.	Toughness Measured	Property Inferred	Method	Formulation[a]	Reference
1	DTE	K_{Ic}	Empirical Correlation	(See Figure A1)	NRL, 10-13
2	K_{Ic}	K_{Id}[b]	Temperature Shift	T_s (°F) = 215 ksi - 1.5 σ_y	Barsom & Rolfe (14) and Barsom (15)
3	K_{Ic}	K_{Id}[c]	Empirical Correlation	$K_{Id} \geq K_{Ic}$	Barsom & Rolfe (14)
4	CVN	K_{Id}	Empirical Correlation	$K_{Id} = [5(E)(CVN)]^{1/2}$	Barsom & Rolfe (14) and Barsom (15)
5	CVN	K_{Ic}[c]	Empirical Correlation	$K_{Ic} = 2.24\sigma_y[\frac{CVN}{\sigma_y} - 0.05]^{1/2}$	Barsom & Rolfe (14)
6	CVN	K_{Ic}[b]	Temperature Shift and Correlation	$T(K_{Ic} = 100 \text{ MPa m}^{1/2}) = 9 + 1.37T(CVN=28J)$ $K_{Ic} = 19(CVN)^{1/2}$	Marandet (2) Sanz (16)
7	NDT	K_{Id}/T-NDT	Approximate Analysis	K_{Id}/T-NDT = 0.7 σyd / 0.5 σyd	Irwin (17) Pellini (18)
8	DTE	NDT	Empirical Correlation	DTE (ft lbs) T - NDT = 0.36σys (ksi) + 55	Lange (19)
9	NDT	K_{Id}[b]	Reference Curve	(See Figure A2)	Pellini (20)
10	NDT	K_{Im}[b]	Reference Curve	(See Figure A2)	Halmetal (4)
11	J_{Ic}	K_{Ic}	Theory	$K_{Ic} = [\frac{J_{Ic} E}{1-\nu^2}]^{1/2}$	Rice (21)
12	J_{Ic}	K_{Im}[c]	Approximate Analysis	$K_{Ic} = 1.5 [\frac{J_{Ic} E}{1-\nu^2}]^{1/2}$	Kahn (22)
13	COD	K_{Ic}	Theoretical Analysis	$K_{Ic} = [2E\sigma y(COD)]^{1/2}$	Rice & Johnson (23)

(a) Formulations for Correlation 2, 4 and 5, are in ksi, ksi√in., and ft lb units, for Correlation 6, in J, MPa m$^{1/2}$

(b) Transition

(c) Shelf

This report takes a first step toward defining the K_{Id} and K_{Im} values for the HY-80 and HY-130 steels and their weld metals appropriate for dynamic LEFM analyses of submerged hull structures. The relative importance of base metal, weld metal and HAZ (heat affected zone) is touched on in Appendix B. The report surveys the limited number K_{Id} values obtained from direct measurements, but draws the bulk of its K_{Id} and K_{Im} estimates from the larger body of CVN-, NDT-, and DTE-measurements. Since LEFM calculations are likely to be concerned with "worst-case" conditions, the emphasis is plased on reasonable, lower bound toughness values at the LAST (lowest anticipated service temperature) which is 30° F for submerged shiphull structure. These lower bound values are based on the specified minimum CVN- and DTE-values listed in Table 2, and the trends displayed by representative heats. In addition, the need for J_{Ic} and K_{Im} measurements for base and weld metals and further verification of the NRL-DTE-KIC correlation are identified.

TABLE 2. TOUGHNESS SPECIFICATIONS FOR HY-GRADE STEEL AND WELDMENT

Grade or Type	Spec. No.	CVN	5/8 DTE
HY-80 Plate	MIL-S-16216H	Longitudinal 50 ft lbs @ -120°F(a)	Transverse 400 ft lbs @ 0°F(b)
HY-100 Plate	MIL-S-16216H	Longitudinal 50 ft lbs @ -120°F(c)	Transverse 450 ft lbs @ 0°F(b)
HY-802 HY-100 Weldments			
11018 Stick electrode	MIL-E-22200/10	50 ft lbs @ 0°F & 70°F	450 ft lbs @ 0°F(b)
12018	MIL-E-22200/1E	20 ft lbs @ -60°F(d)	
MIL-100S, 110S 120S Wire	MIL-E-23765	50 ft lbs @ -60°F	450 ft lbs @ 0°F(b) for 120S only
Type M188 Submerged arc electrode	MIL-E-24355	20 ft lbs @ -60 / 50 ft lbs @ 30°F	
HY-130	MIL-E-24355	Transverse 60 ft lbs @ 0°F & 70°F	Transverse 500 ft lbs @ 0°F(b)
HY-130 Weldmental			
Type MIL-4105 Bare, Solid Wire	MIL-E-24355A		500 ft lbs @ 30°F(e)
14018 Stick electrode	MIL-E-22200/9A		475 ft lbs @ 30°F(e)

(a) 30 ft lbs for sections of 6 inches thick

(b) optional

(c) 30 ft lbs for sections over 4 inches thick

(d) for yield strength 95 ksi - 107 ksi

(e) for yield strength 135 ksi - 150 ksi

DYNAMIC FRACTURE TOUGHNESS PROPERTIES

HY-80 Base Plate

Existing direct measurements and estimates of K_{Id} ($K_I \sim 10^5$ ksi $\sqrt{\text{in.}}$ sec^{-1}) derived from K_{IC}-, CVN-, and DTE-measurements are summarized in Figure 1. The CVN curves in Figure 2 illustrate that the NDT temperature for this grade corresponds roughly with the midpoint of the CVN energy transition. An estimate of the lower bound, the curve LB, just satisfies the specified minimum CVN value (50 ft lbs at -120° F) and reflects the likely temperature variation.

The CVN curves and the K_{Id} values inferred form them in Figure 1 (of the Correlations 4 and 5 in Table 1), illustrate that HY-80 displays ductile, upper shelf-level behavior at the LAST. The K_{Id} estimates at the LAST are derived from CVN and DTE measurements (Correlations 3, 1, and 5 in Table 1). No crack arrest toughness (K_{Im}) measurements have so far been performed on HY-80; the estimates in Table 3 are based on the highest NDT temperature and the $\dfrac{K_{Im}}{\sigma_{Yd}}$ reference curve in Figure A-2.

HY-130 Base Plate

Direct measurements of K_{Id} are produced in Figure 3, together with K_{Id} estimates based on K_{Ic} (Correlation 2), CVN (Correlation 4) and DTE (Correlation 1). Representative CVN and DTE transition curves are reproduced in Figures 4 and 5. These curves illustrate that HY-130 grade, like the HY-80, displays ductile shelf behavior at the LAST.

The specified minimum CVN for this material (60 ft lbs at 30° F) provides one basis for estimating the lower bound K_{Ic} and K_{Id} values. The corresponding DTE provides another. Since the correlation between CVN and DTE is approximate, it further reduces the lower bound value of DTE associated with the LAST to 300 ft lbs. This is illustrated in Figure 6. No crack arrest toughness measurements have so far been performed on HY-130 steel. The estimate of K_{Im} quoted in Table 3 are based on the $\dfrac{K_{Im}}{\sigma_{Yd}}$ reference curve in Figure A-2.
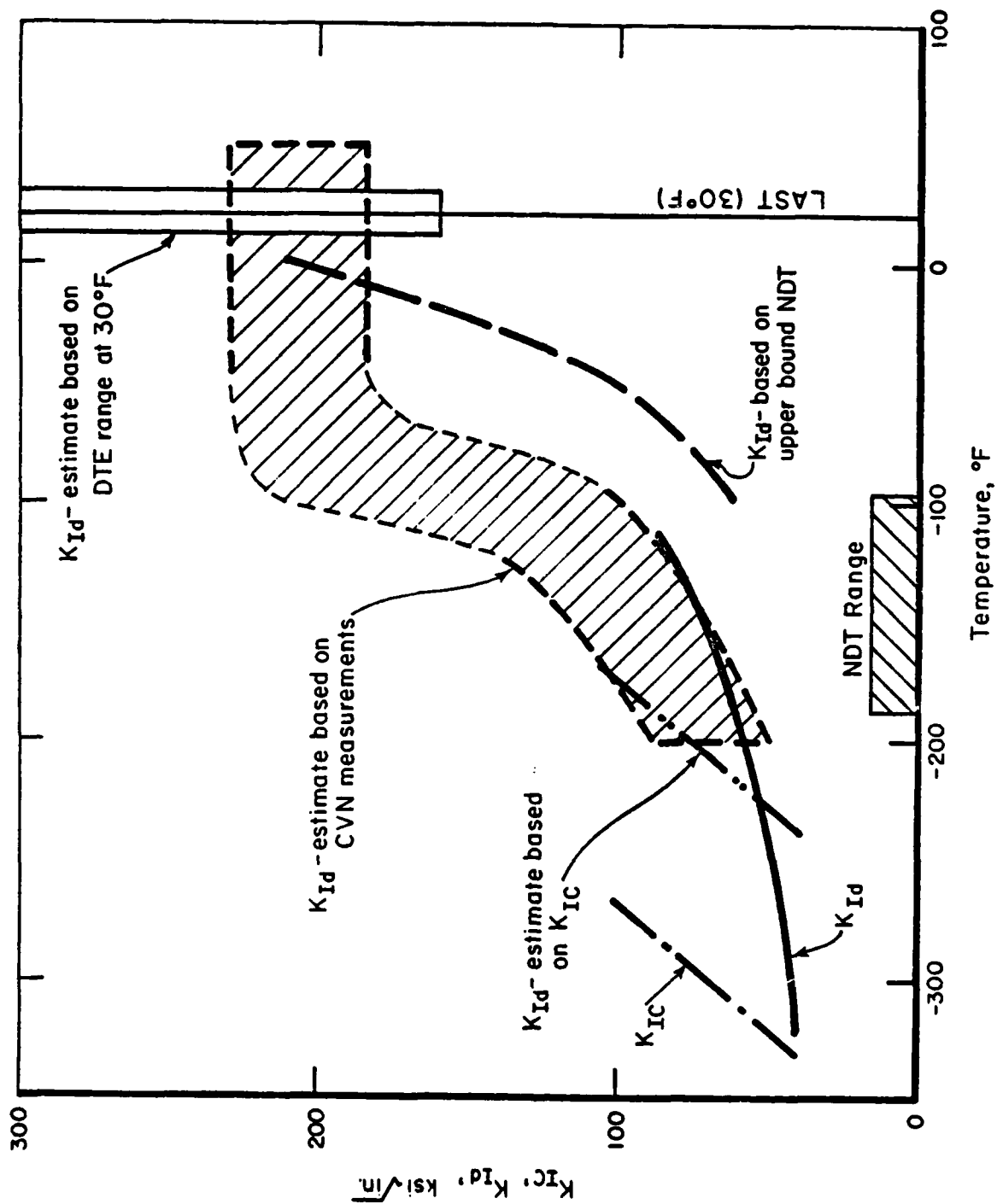
FIGURE 1. SUMMARY OF K_{Id} MEASUREMENTS FOR HY-80 STEEL AND K_{Id} ESTIMATES BASED ON K_{Ic}, CVN, AND DTE MEASUREMENTS, ATTER, SHOEMAKER AND ROLFE(24), BARSON(25), PUZAK(26), AND GOODE ET AL(27). THE SOURCE OF CVN AND NDT DATA ARE IDENTIFIED IN FIGURE 2.

FIGURE 2. CVN ENERGY AND NDT VALUES FOR HY-80 STEEL AFTER PUZAK AND BABECKI(29), PUZAK(28)
BARSOM AND ROLFE(14), AND BABECKI AND PUZAK(30)

TABLE 3. SUMMARY OF ESTIMATES OF TYPICAL AND
LOWER BOUND TOUGHNESS PARAMETERS FOR
HY-80 AND HY-130 STEEL AND WELDMETALS
AT THE LAST (30°F)

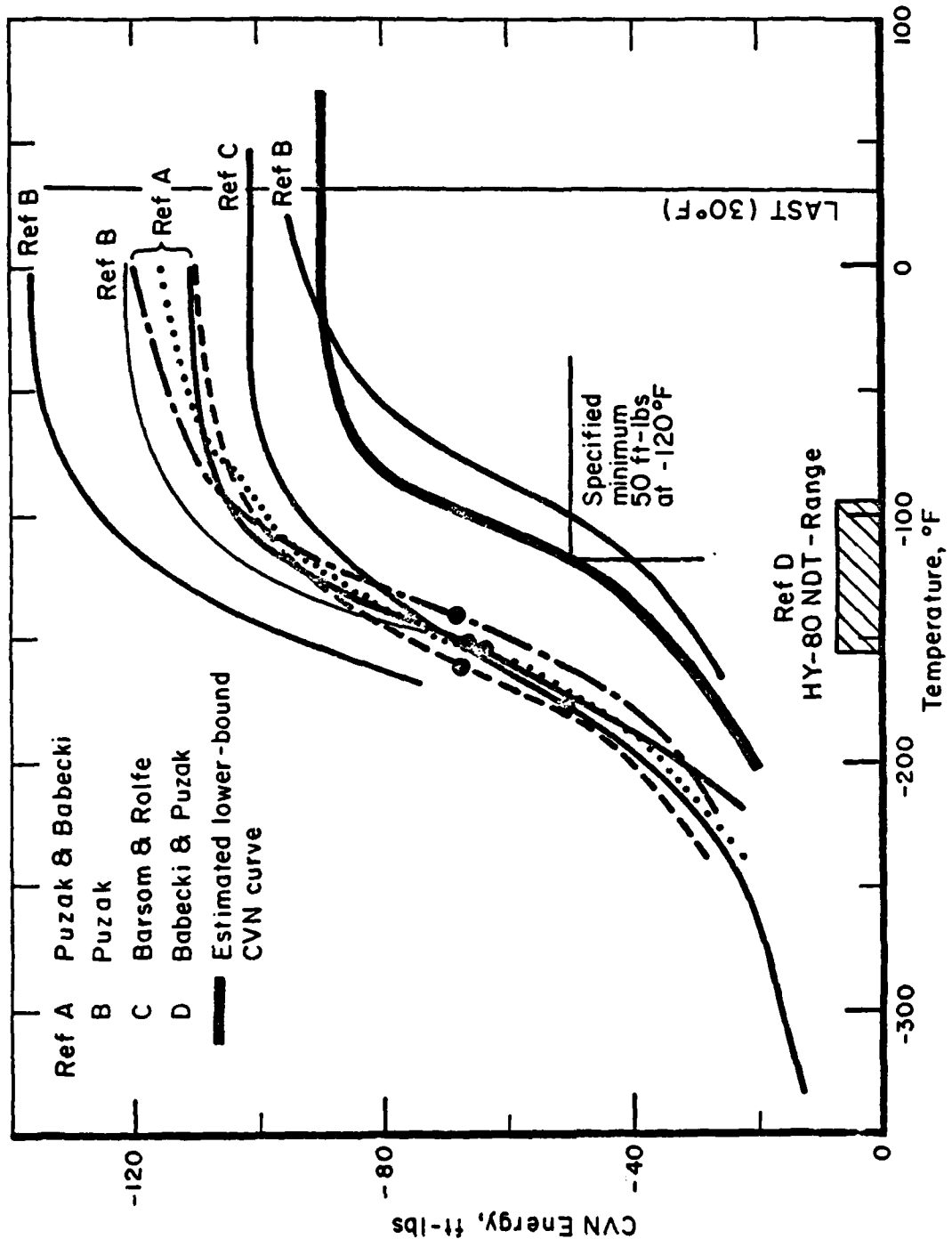| Material	Toughness Parameter	Typical Value	Lowerbound Estimate
HY-80	NDT, °F	-150	-100
	CVN, ft lbs	110	90
	5/8 in. DTE, ft lbs	~ 800	420
	K_{Ic}, ksi in.	200-250	160[a]
	K_{Id}, ksi in.	$\geq$ 200-250	$\geq$ 160[a]
	K_{Im}, ksi in.	~ 174	~143
MIL-11018 Type	NDT, °F	-	-20
HY-80 Weldmetal	CVN, ft lbs	-	42
	5/8 in. DTE, ft lbs	~ 450	260
	K_{Ic}, ksi in.	~ 160	120
	K_{Id}, ksi in.	-	~ 80
	K_{Im}, ksi in.	-	~ 92
HY-130	NDT, °F	-120	-60
	CVN, ft lbs	~ 80	60
	5/8 in. DTE, ft lbs	550	330
	K_{Ic}, ksi in.	~185[a]	135[a]
	K_{Ia}, ksi in.	~185[a]	$\geq$ 135[a]
	K_{Im}, ksi in.	~229	~ 174
MIL-1405, GMA Type HY-130 Weldmetal	NDT, °F	-110	-60
	CVN, ft lbs	-	-
	5/8 in. DTE, ft lbs	~ 550	340
	K_{Ic}, ksi in.	~ 175	140[a]
	K_{Id}, ksi in.	~ 175	140[a]
	K_{Im}, ksi in.	~220	~ 174

(a) based on DTE
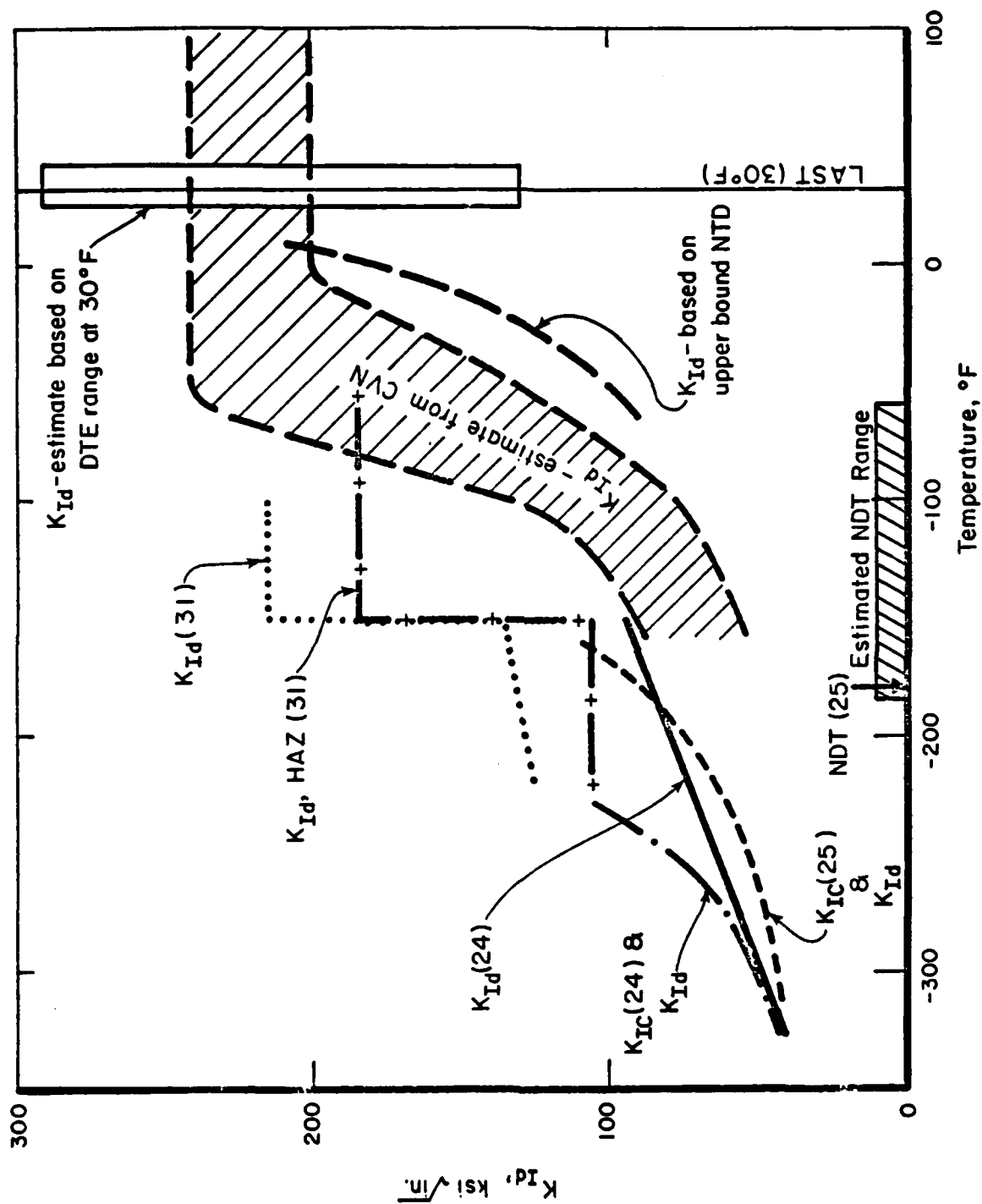
FIGURE 3. SUMMARY OF K_{Id} MEASUREMENTS FOR HY-130 STEEL AND K_{Id} ESTIMATES BASED ON K_{IC}, CVN, AND DTE MEASUREMENTS, ATTER, SHOEMAKER AND ROLFE(24), BARSOM(25) AND PENSE(31), AND PUZAK(32)
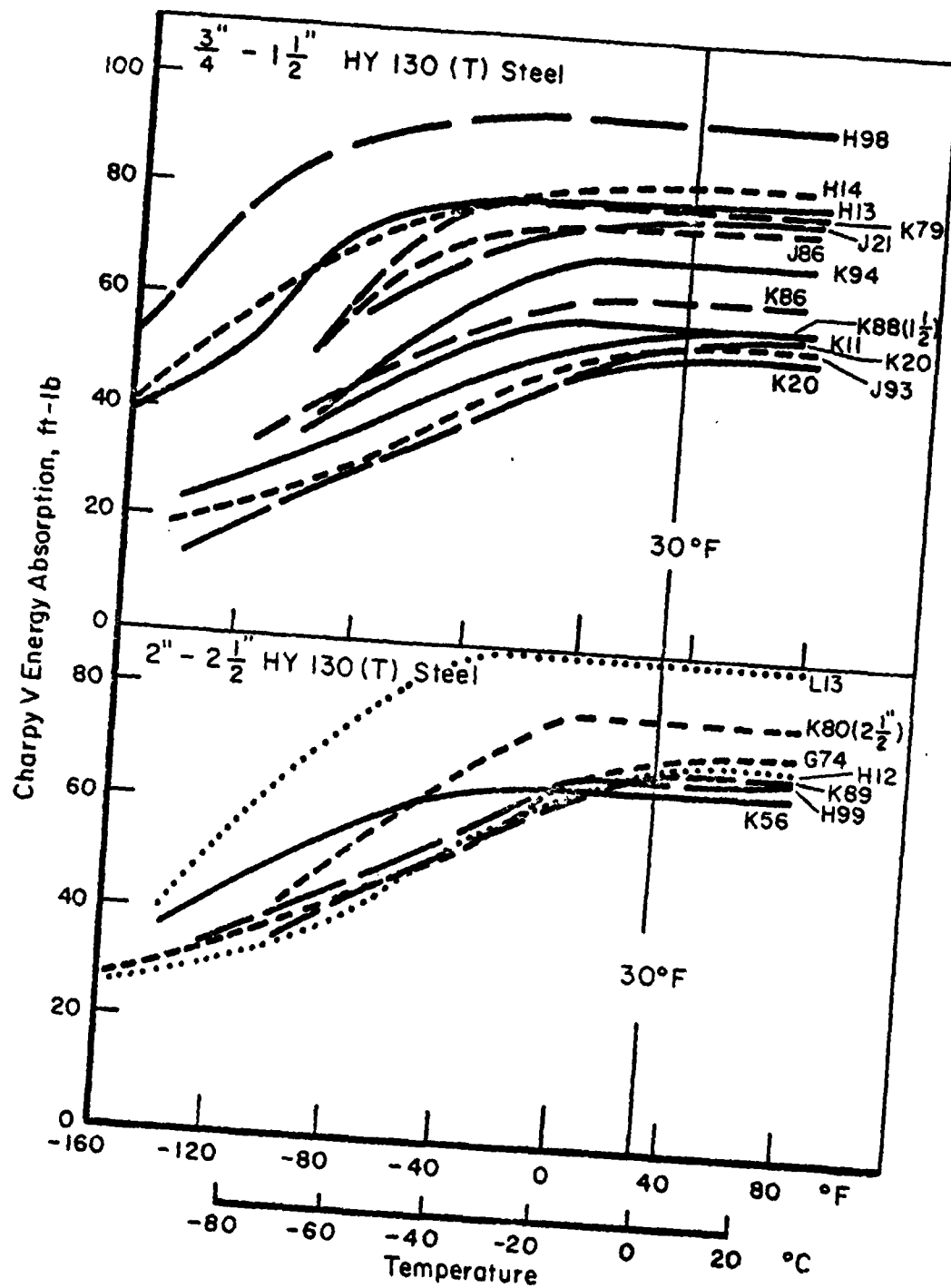
FIGURE 4. CVN ENERGY VALUES FOR HY-130 STEEL PLATES IN THE "WEAK"
(WR) ORIENTATION AFTER PUZAK(32)

-13-
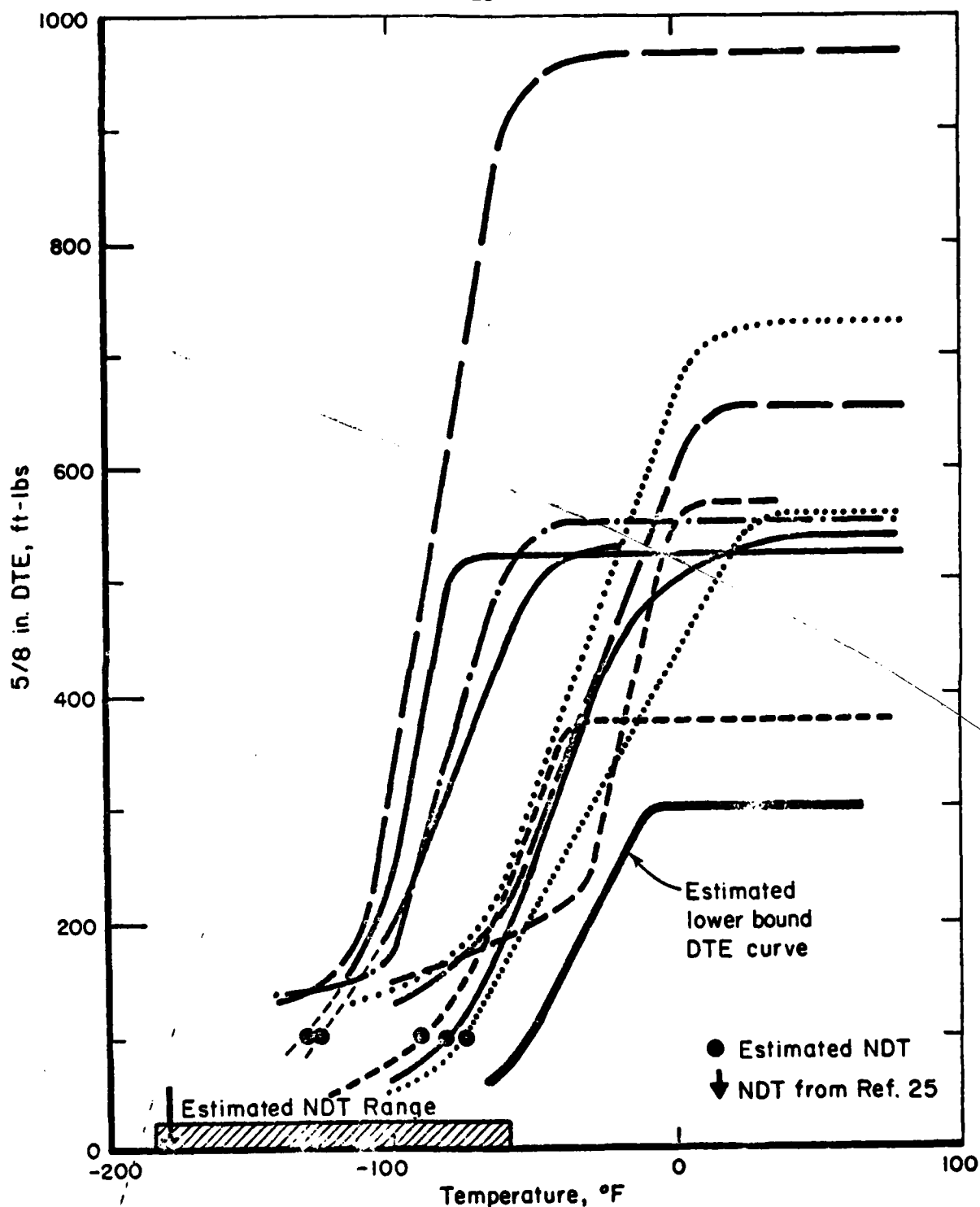
FIGURE 5. DTE ENERGY VALUES FOR HY-130 STEEL PLATES OF DIFFERENT THICKNESSES AFTER
PUZAK(32). THE 1 IN., 1.5 IN., 2 IN., AND 2.5 IN. DTE VALUES HAVE BEEN
REDUCED BY FACTORS OF 8, 15, 22.6, AND 29 TO MAKE THEM COMPARABLE TO 5/8
IN. DTE VALUES. THE ESTIMATED NDT TEMPERATURES ARE OBTAINED BY RELATING
IT TO THE TEMPERATURE CORRESPONDING TO A 5/8 IN. DTE OF 100 FT LBS(19).
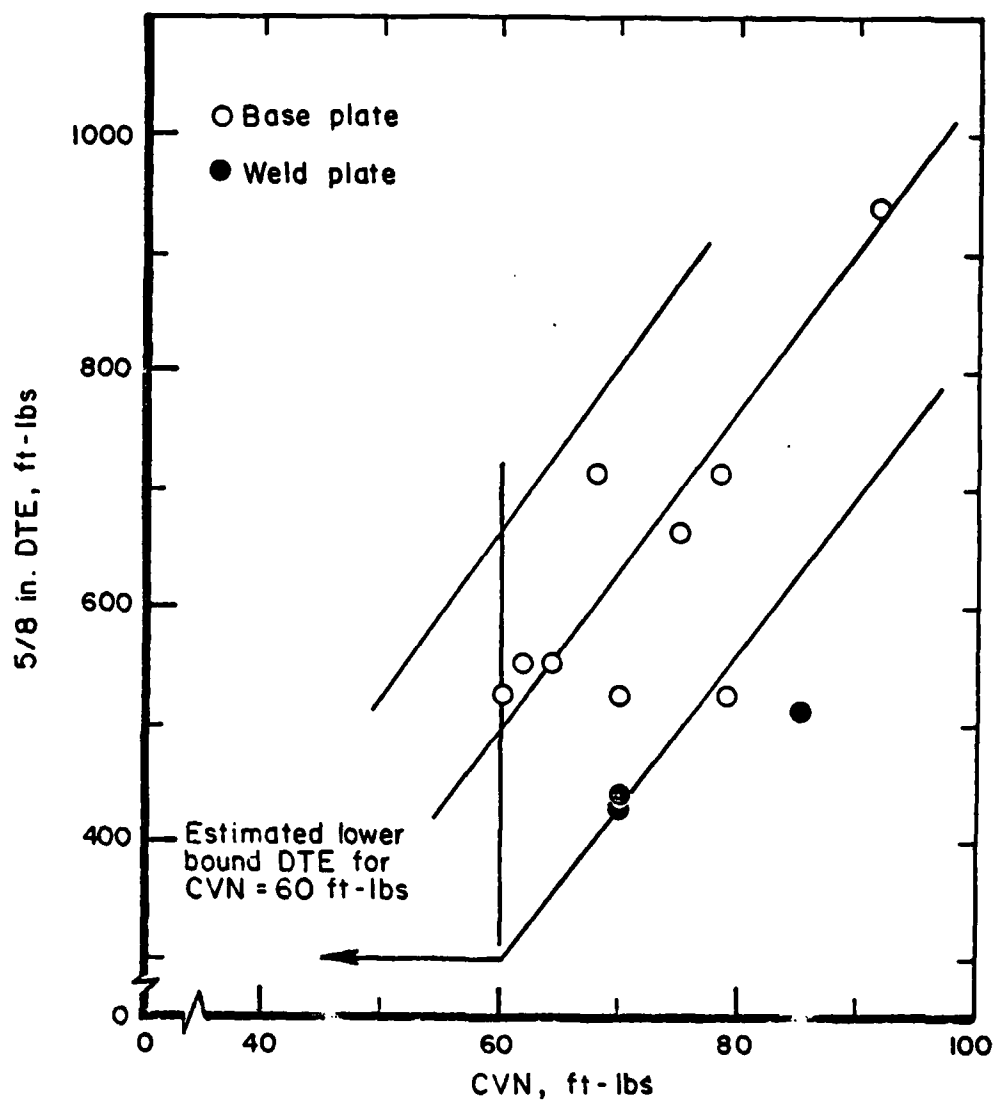
FIGURE 6. CORRELATION BETWEEN CORRESPONDING CVN AND 5/8 IN. DTE VALUES MEASURED ON THE DUCTILE SHELF FOR THE HY-130 STEELS [DATA OF FIGURES 4 AND 5 AFTER PUZAK(32)]. THE SCATTERBAND REFLECTS THE APPROXIMATE NATURE OF THE CVN DTE CORRELATION AND INDICATES THAT A DTE VALUE MAYBE AS LOW AS 300 FT LBS FOR A CVN OF 60 FT LBS

Weld Metals

The most telling toughness evaluations of HY grade weld metal--weld metal and HAZ--are obtained using the explosion bulge test[28,29,36,37]. While this is a very severe test of performance, it has not been correlated with absolute measures of toughness like K_{Ic} or K_{Id}. The only direct LEFM-type tests are the few measurements of the COD for a HY-130 plate and HAZ that have recently been reported by Pense[31]. These are converted to K_{Id} estimates in Figure 3 (Correlation 13). Estimates of K_{Id} must be drawn from the body of CVN and DTE measurements of weld metal which have been developed by NRL. These studies show that, while HY-80 and HY-130 display near ductile shelf-level behavior on the average, some lower bound values fall in the transition range.

Figure 7 reproduces lower bound 1 inch DTE curves from a limited sampling of welds produced by the Portsmouth and NSRDC-A facilities. This set of results shows that the lowest value at the LAST is 260 ft lbs (5/8 inch DTE) for a vertical position weld. The CVN curves for this class of weld metal, shown in Figure 8, indicate a lower bound CVN value of 42 ft lbs at the LAST for weldment just meeting the 20 ft lbs at -60° F minimum specificatio Figure A-3 indicates that 42 ft lbs (CVN) corresponds with about 2000 ft ɔ inches, 1 inch DTE, or 250 ft lbs -5/8 inch DTE. This is in agreement with the 260 ft lb value mentioned above. Corresponding K_{Id} estimates are listed in Table 3. The K_{Im} value is based on the NDT estimate of Figure 7 and the K_{Im}/σ_{Yd} reference curve of Figure A-2.

Results for a large number of HY-130 welds of the Mil-140S weld metal GMA type are summarized in Figure 9. The lower bound is an indication of the poorest quality encountered in practice. These results are for 2 inch DT specimens. Estimates of the corresponding 5/8 inch DT behavior are obtained by shifting the curve about 40° F[33] and reducing the energy by a factor of 22.6. These results suggest a lower bound of 340 ft lbs 5/8 inch DTE at the LAST and a maximum NDT temperature of about -60° F. The 340 ft lbs value is significantly lower than 500 ft lbs @ 30° F specified minimum for this type of weld metal (see Table 2). The corresponding K_{Id} estimate (Correlation 1) and K_{Im} estimate (Figure A-2) are listed in Table 3.
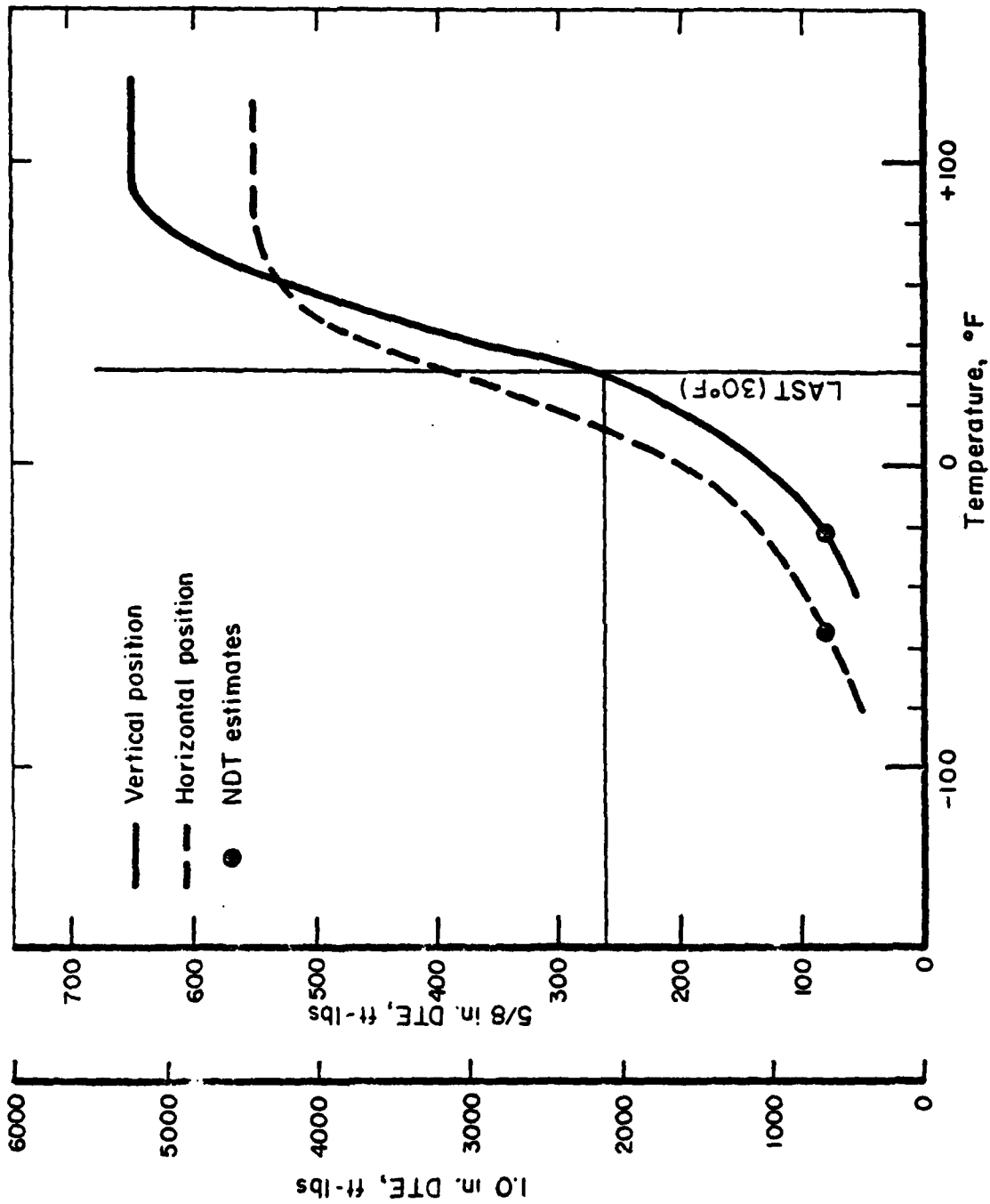
FIGURE 7. LOWER BOUND (IN TERMS OF TOUGHNESS) 1 IN. DTE CURVES FROM A LIMITED SAMPLING OF MIL 11018 WELDS PRODUCED BY THE PORTSMOUTH AND NSRDC-A FACILITIES AFTER PELLINI (33). THE NDT ESTIMATES ARE BASED ON CORRELATION 8 (TABLE 1).
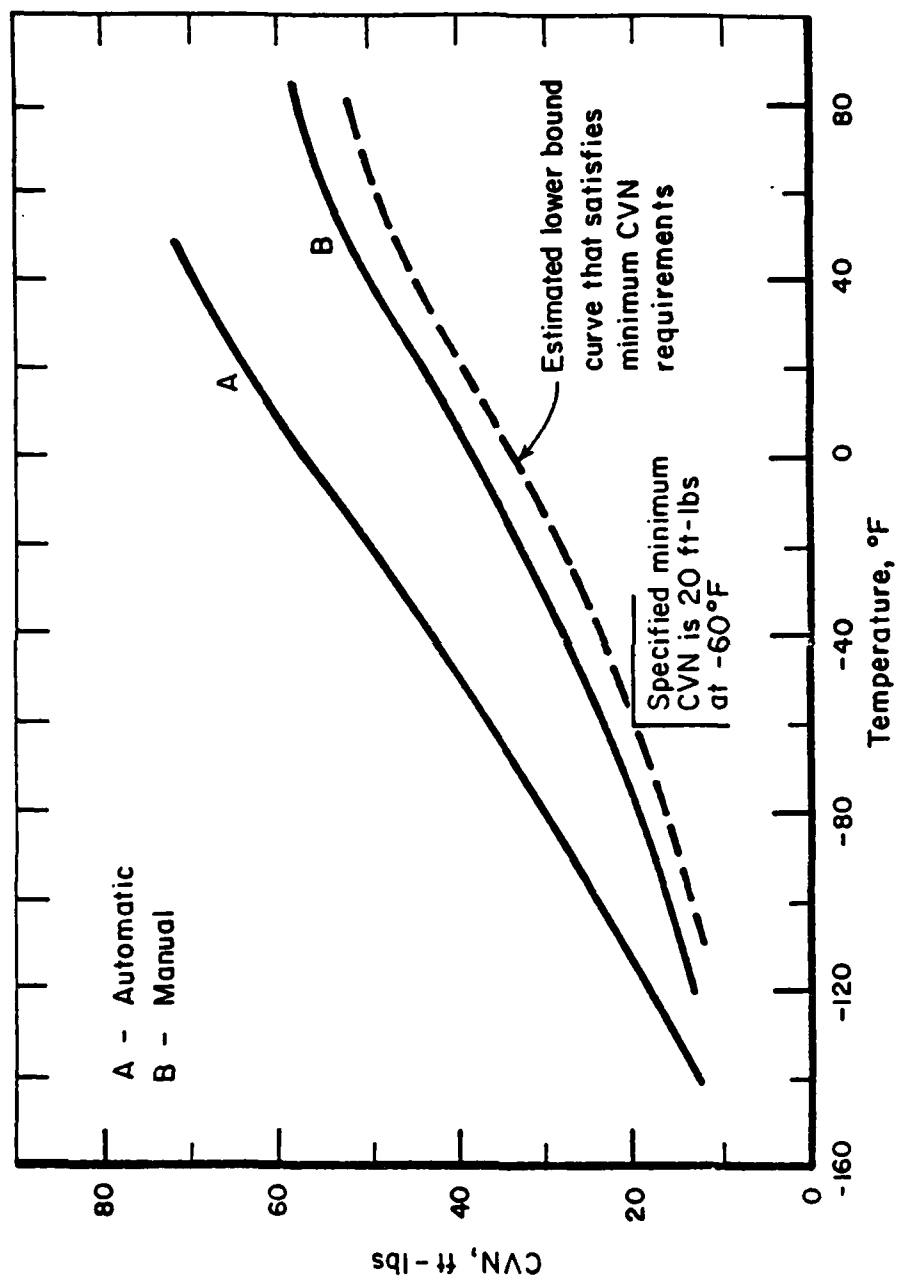
FIGURE 8. CVN CURVES FOR HY-80 WELD D METAL FOR (A) MIL-B-88 AUTOMATIC INERT-GAS-SHIELDED METAL ARC WELD AND (B) MIL-11018 MANUAL WELD DEPOSITS
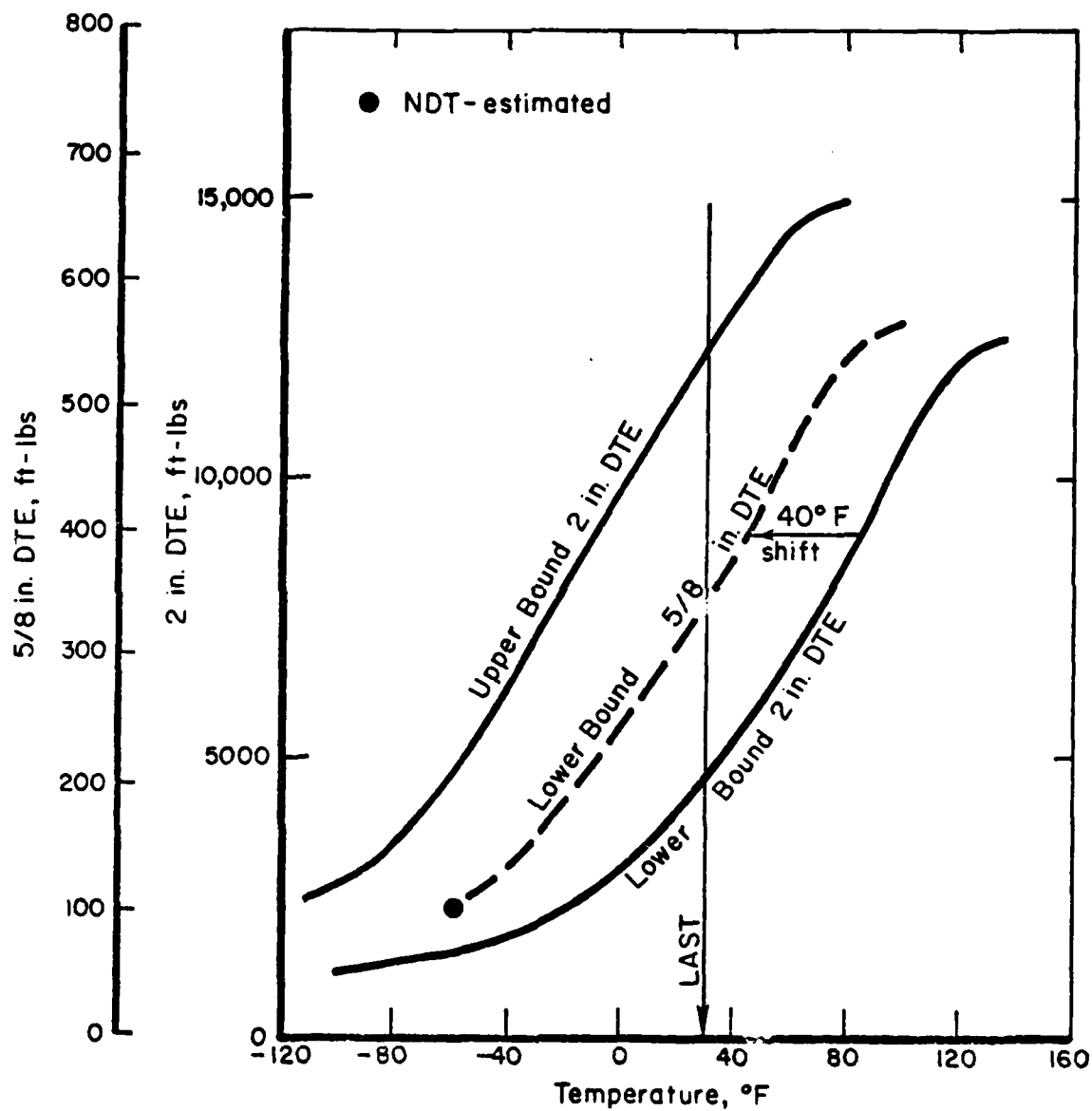
FIGURE 9. ENVELOPE OF 2 IN. DTE VALUES FOR HY-130 TYPE GMA WELDS
AFTER LANGE(34,35). THE NDT ESTIMATE IS BASED ON
CORRELATION 8 IN TABLE 1

DISCUSSION OF FINDINGS

The lower bound K_{Id} values for the HY-80 and HY-130 steel and weld metals, listed in Table 3, tend to fall short of the toughness levels of 200 MPam$^{1/2}$ - 300 MPam$^{1/2}$ that are usually associated with ductile, shelf-level performance. This may be a consequence of the lack of direct measurements for these materials near the LAST, which forces reliance on approximate (and possibly conservative) DTE and CVN correlations, whose precision for HY-grades and steels under high toughness levels is not well established. Some indication of the uncertainty connected with the NRL-DTE-K_{Ic} correlation can be found in Appendix A.

Where minimum toughness levels are specified in terms of CVN-values, the approximate nature of the CVN-DTE correlation tends to reduce lower bound estimates of K_{Id} via DTE even further. The K_{Im} estimates in Table 3 are particularly uncertain and speculative. No K_{Im} measurements are available for HY-grades that can be used to test the reference curve procedure. In addition, the K_{Id} estimates do not reflect the rising resistance to fracture with crack extension (R-curve behavior). The positive K-dependence, which adds significantly to load carrying capacity when such extension proceeds with shelf-level toughness values, is also not included. Finally, the present lower bound estimates were obtained without: (i) the precise criteria, (ii) the statistical treatments of the data, and, in some cases, (iii) the sufficiently large data base, which is essential for critical structural analyses.

Bearing those limitations in mind, it is still instructive to note that approximate lower bound values of K_{Id}/σ_Y are $2\sqrt{in.}$ for HY-80 steel and $1\sqrt{in.}$ for HY-130 steel and the two weld metals. The $2\sqrt{in.}$ K_{Id}/σ_Y value indicates that a 4 inch thick plate of HY-80 satisfies the (YC) criterion (essentially, leak-before-break at general yield), while a $1\sqrt{in.}$ value indicates this criterion is only satisfied by HY-130 and the two weldments for 1 inch thick plate. It would therefore appear that the HY-80 plate is substantially more resistant to fracture under dynamic loading than the other three material grades.

The reliability of future calculations of hull-structure fracture behavior under dynamic loading will be enhanced by a better resolution of the K_{Id} and K_{Im} toughness parameters. This will require direct measures of K_{Id} and K_{Im} that can be used to calibrate DTE and CVN values at the LAST. The task of measuring the very large K_{Id} and K_{Im} values is now greatly reduced because K_{Ic} values can be derived from J_{Ic} measurements. These measurements use small test pieces under an ASTM procedure which is close to standardization. Since shelf level K_{Id} values are likely to be 15-25% larger than K_{Ic}*, J_{Ic} values also offer lower bound estimates of K_{Id}.

More research is needed to define the $\dot{K}_I$ dependence of these values, but this should not be a formidable problem. Crack arrest toughness values can also be obtained from J_{Ic} since $K_{Im} \doteq K_{Ic}$ on the shelf. Finally, J_{Ic} determinations can be combined with measurements of the R-curve which offer the possibility of describing stable growth and instability in addition to the onset of crack extension. For weld metal, the existing test procedures make it possible to measure 100 ksi in.$^{1/2} \lesssim K_{Im} \lesssim 150$ ksi in.$^{1/2}$ in the transition range. Such measurements are needed to establish the reliability of a K_{Im} reference curve based on NDT or other procedures for estimating K_{Im} from more easily measured properties.

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* Compare shelf-level CVN values for statistically and dynamically loaded specimens in Reference (14).

CONCLUSIONS

A survey of dynamic fracture toughness properties suitable for analyses of crack propagation in submerged ship hulls has been conducted. This survey has concentrated on HY-80 and HY-130 steels and their weld metals at 30° F, the lowest anticipated service temperature (LAST) for these materials. The key findings of the survey are:

1. The HY-80 and HY-130 grades satisfying specified minimum toughness requirements display ductile, shelf-level behavior at the LAST. Weld metals of these grades satisfying minimum toughness requirements operate closer to the lower part of the transition region.

2. A lower bound value of the ratio K_{Id}/σ_Y is estimated to be 2 inches$^{1/2}$ for HY-80 at the LAST. For HY-130 and both the HY-80 and HY-130 weld metals, a lower bound value of this ratio is about 1 inch$^{1/2}$*. It appears from these figures that HY-80 steel is substantially more resistant to fracture under dynamic loading than are the other three grades examined.

3. Lower bound K_{Id} estimates in Table 3 may underestimate the toughness of the HY-steels and weld metals because of the dearth of direct measurements of these quantities and consequent uncertainties in the correlations on which the estimates are based. Lower bound estimates of the crack arrest toughness, K_{Im} in Table 3 are particularly uncertain and speculative because no measurements of this quantity are available for any HY-grades. Direct measurements of K_{Id} and K_{Im} are feasible and should be attempted.

It can be concluded that criteria for "worst-case" lower bound toughness values should be established. These should be applied to statistical treatments of the measurements to improve the definition of lower bound toughness values.

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* This value is based upon plate purchase to a CVN-60 ft-lb requirement and the CVN-DT Correlation in Figures 6 and A3. If the optional DTE 500 ft-lb at 0°F requirement is used, the minimum K_{Id}/σ_Y ratio for the plate would be 1.6 which is close to a general yield condition for 2 in.-plate.

Also, measurements of shelf value J_{IC} and J_R curves should be performed with the aim of improving and validating the NRL DTE-K_{IC} correlation and to provide more reliable, lower bound estimates of K_{Id} and K_{Im}. Finally, the crack arrest toughness properties of weld metals with toughness levels close to the specified minimum should be measured at the LAST with the aim of establishing a suitable estimation scheme.

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APPENDIX A

CORRELATIONS BETWEEN FRACTURE TOUGHNESS
PARAMETERS AND DTE, NDT, AND CVN

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The reliability of different correlations between LEFM fracture toughness parameters and DTE, NDT, and CVN values is examined in detail in Reference 10. Some points, which are not treated in that reference, but are important in the context of this report are discussed below.

Correlations with DTE

The data, which were used to construct the NRL DTE-K_{Ic} correlation are identified in Figure A-1. Relatively few measurements were originally performed on medium strength steels in the transition range. The K_{Id} portion of the curve was constructed later, and is based on DTE values at the NDT, and the assumed relation $K_{Id}/\sigma_{Yd} = 0.5$ in.[19], which is approximate. The curve for the A533B steel is based on 5/8 in.-DTE measurements performed at NRL[37], and K_{Ic} measurements on a number of (different) heats of [533B in Reference 7. The K_{Ic} values predicted by the A533B curve are about 20-30% smaller than the one obtained from the NRL curve. To be conservative, the A533B curve is used to estimate K_{Ic} and K_{Id} values on this report.

Correlation with NDT

The concept of indexing the toughness transition curve to the NDI temperature, which has been championed by Pellini, is widely used. Recently, Pellini has proposed a K_{Id} reference curve for medium strength steels indexed to the NDT[20]. Pellini's curve relates the absolute toughness, K_{Id}, to the relative temperature (T-TNDT). Since the fracture toughness at the NDT-temperature is believed to vary with yield strength[18], an attempt has been made here to make it more general by expressing the relation in terms of K_{Id}/σ_{Yd}, with the value of this ratio $(K_{Id}/\sigma_{Yd})NDT = 0.6\sqrt{in}$. The resulting reference curve is shown in Figure A-2. Estimates of K_{Id} based on the upper bound NDI
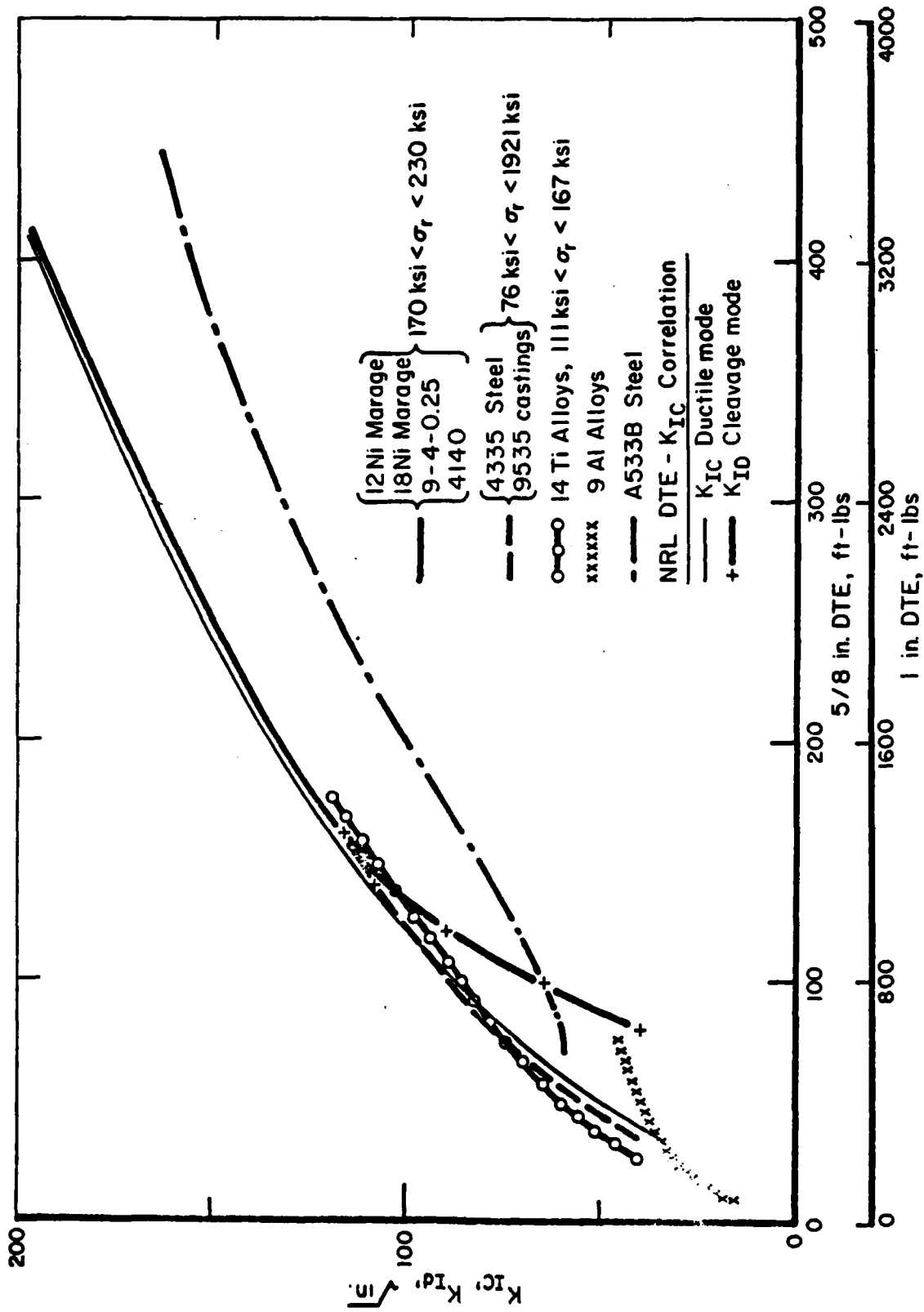
FIGURE A1.   SUMMARY OF DATA COMPARING THE NRL DTE K_{Ic} CORRELATION(10-13).   RESULTS FOR
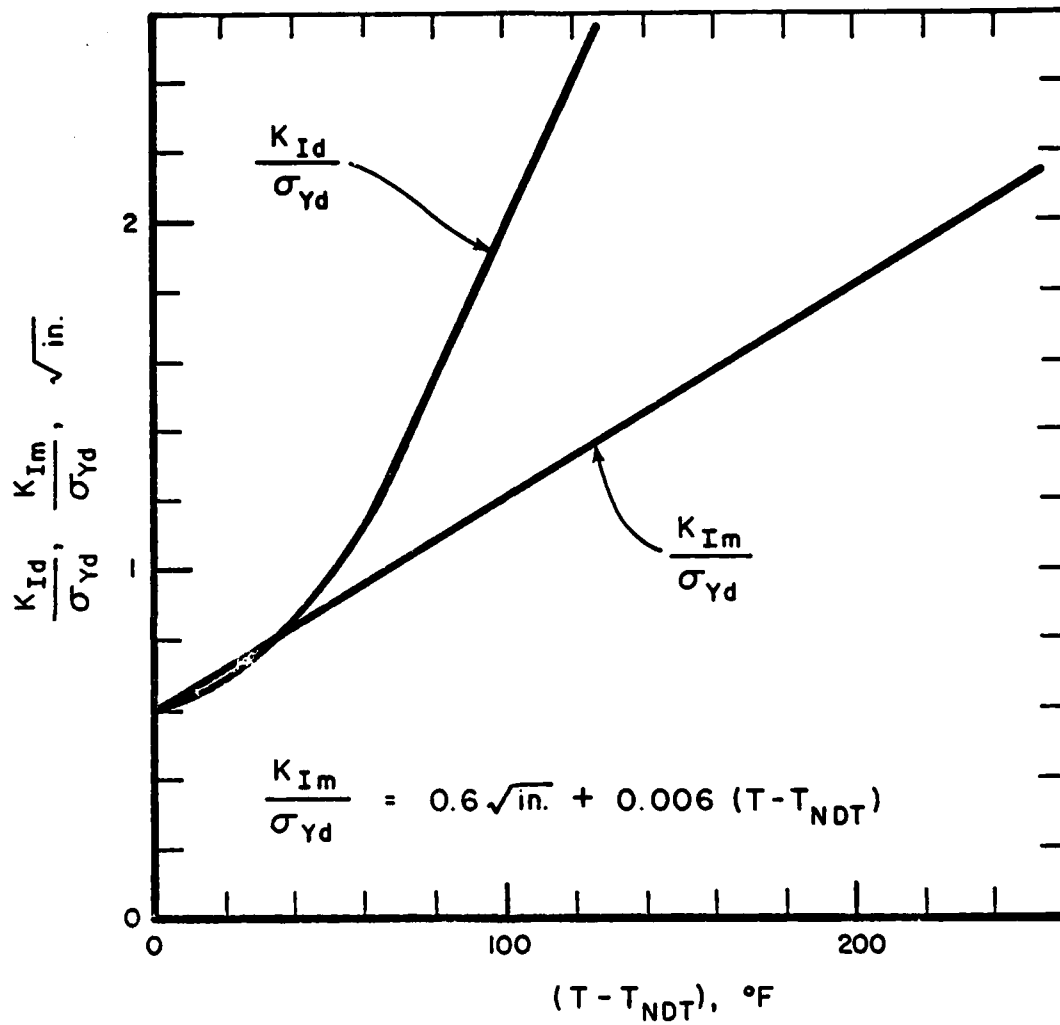A533B ARE FROM REFERENCE 7 AND 37

FIGURE A2. PROPOSED "REFERENCE" CURVES RELATING K_{Id} AND K_{Im} TO THE TEMPERATURE RELATIVE TO THE NDT AFTER PELLINI(20) AND HAHN ET AL(7)

and obtained in this way are included in Figures 1 and 3. The same reasoning has been used to generalize K_{Ia} measurements performed on A533B[7]. The K_{Im}/σ_{Yd} reference curve shown in Figure A-2 is based on K_{Ia} values one standard deviations below the average[7]. It should be noted that while this method of estimating K_{Im} is unproven, and speculative, it is the only approach currently available for estimating crack arrest toughness values.

Estimates of σ_{Yd} were obtained using the approximation $\sigma_{Yd} = \sigma_Y +$ 25 ksi, where σ_Y is the conventional yield stress and σ_{Yd} is the yield stress for rates of straining $\varepsilon p \simeq 10^3$ sec^{-1}.

Correlation with CVN

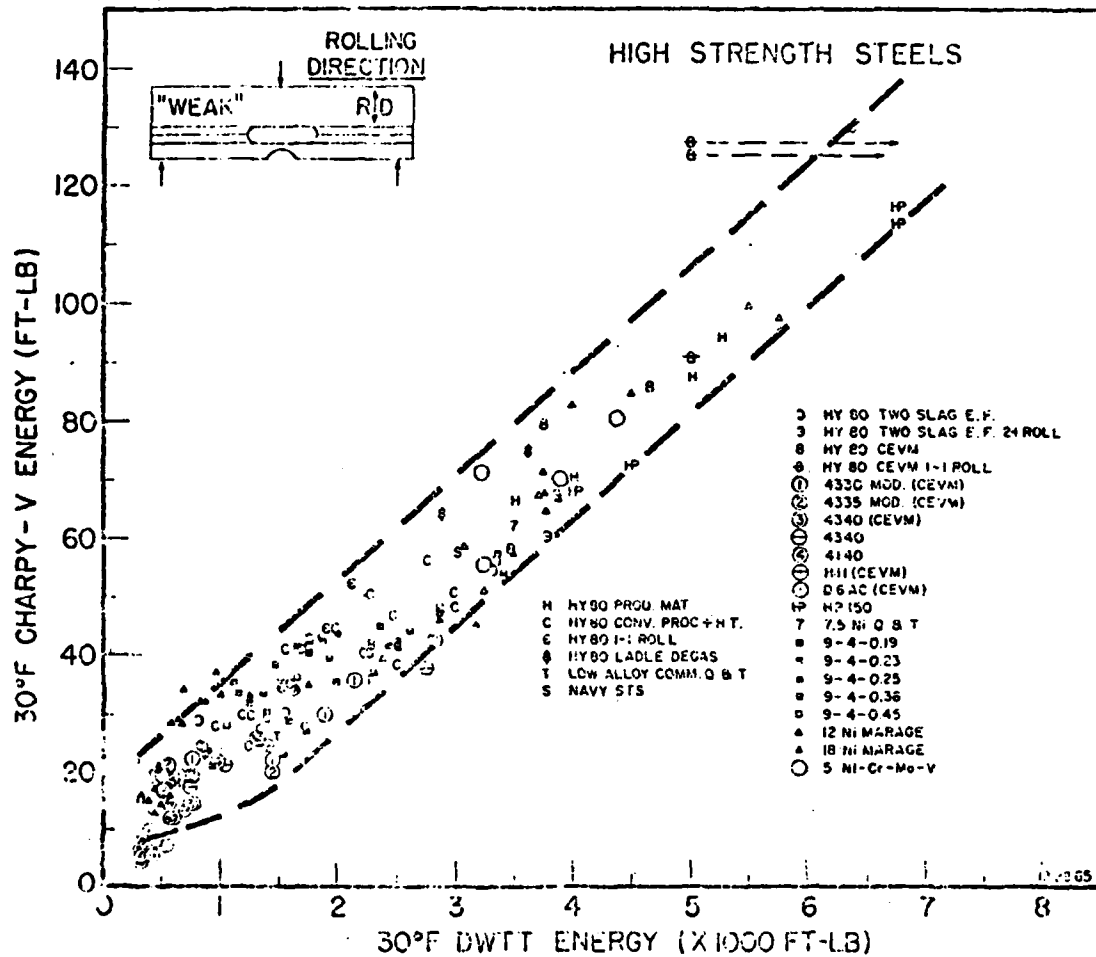A correlation between shelf level CVN and DTE values developed at NRL[27] is reproduced in Figure A-3.

FIGURE A3. CORRELATION OF DWTT AND C$_V$ DATA FOR ALL HIGH STRENGTH
STEELS TESTED. THE DATA IS FOR "SHELF ENERGIES" I.E.,
AT TEST TEMPERATURES WHERE THE FRACTURES ARE FULLY
DUCTILE, AFTER GOODE ET AL(27)

APPENDIX B

WELD STRUCTURE

APPENDIX B

WELD STRUCTURE

The toughness of the HAZ (Heat Affected Zone) of a weld (B-1) can be lower than that of the base metal or the weld metal (see Figure B-1). However, because the HAZ is usually narrow, and the weld tapered, a crack initiated in the HAZ of the butt weld will tend to propagate into the base metal or the weld metal. Examples of this for a T-frame attachment are illustrated in Figure B-2. Explosion bulge tests provide further verification that the HAZ does not provide an easy path for a fracture. These considerations provide justification for focusing on the base metal and the weld metal and neglecting the HAZ in lower bound toughness assessments of welded structure.
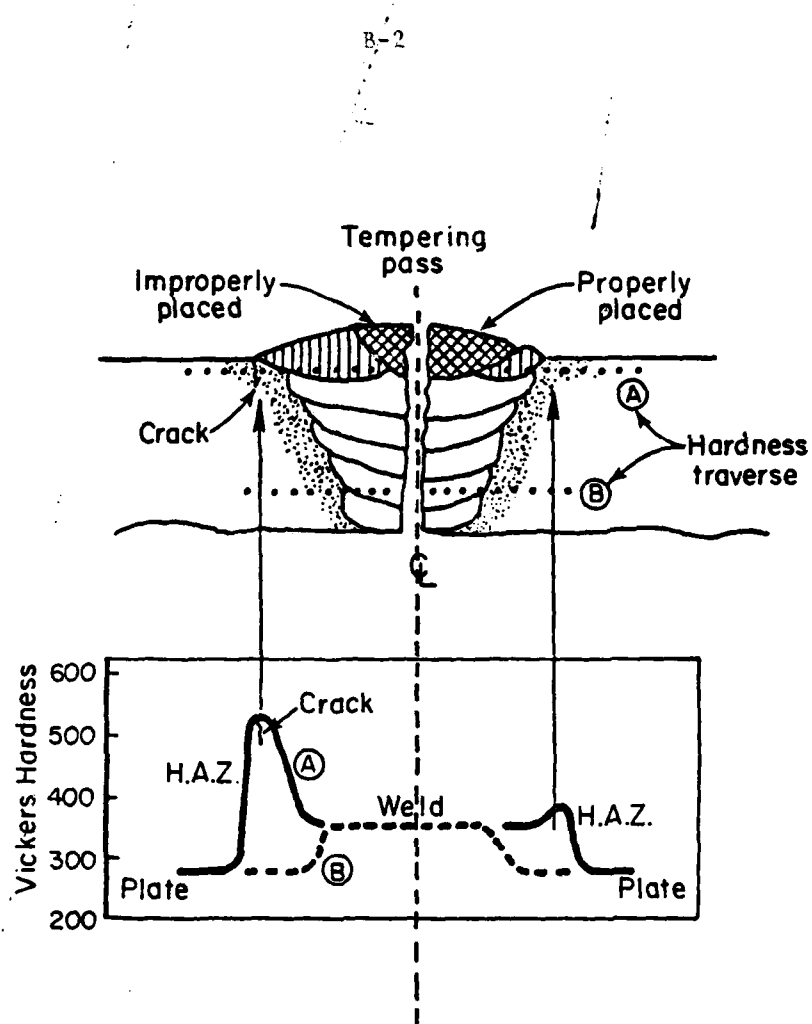
FIGURE B1. SCHEMATIC OF THE STRUCTURE OF A BUTT WELD AFTER
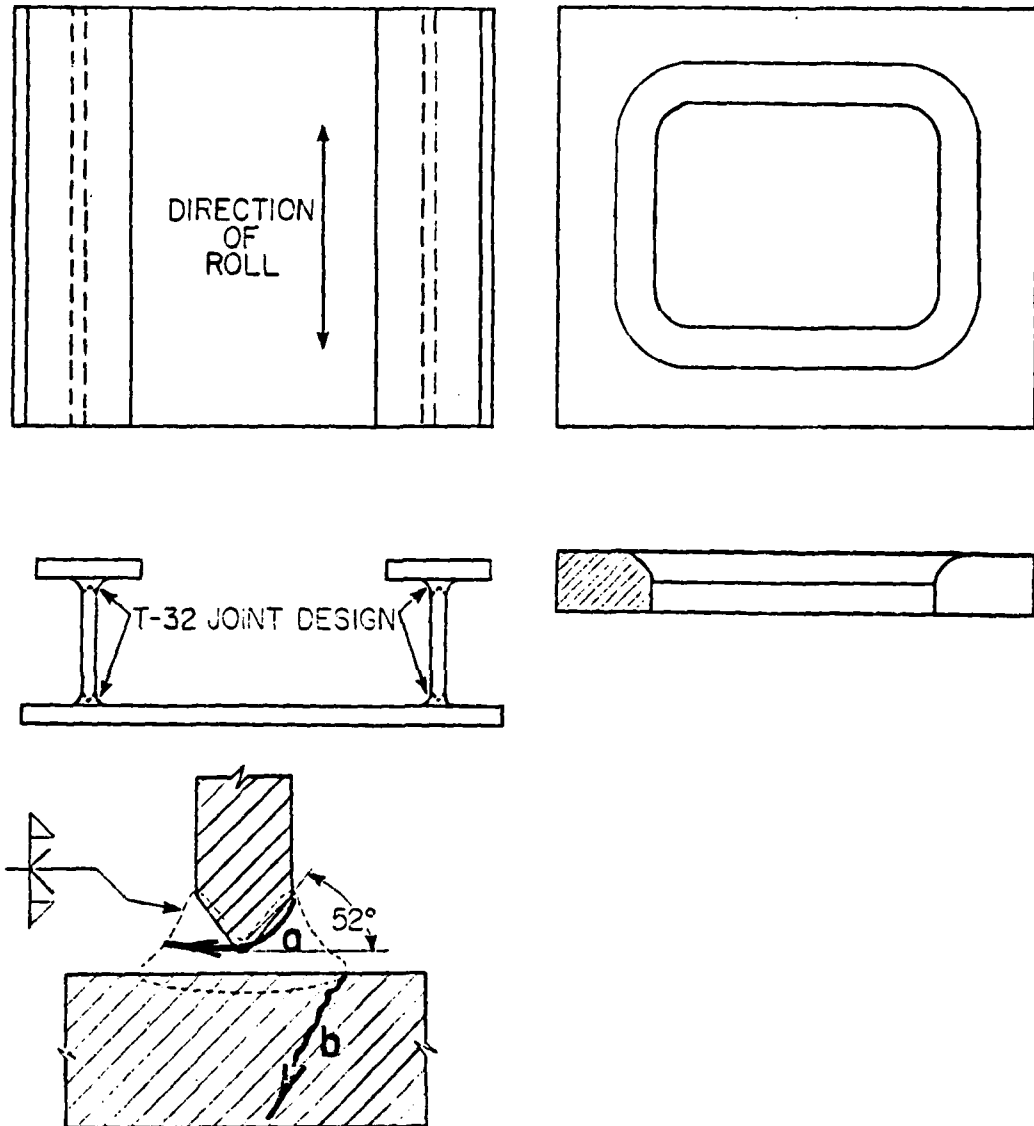PELLINI AND PUZAK(35)

FIGURE B-2. EXPLOSION TEST OF MODEL SIMULATING RESTRAINT OF EXTERNAL FRAMING: SPECIMENS AND WELD JOINT DESIGN (LEFT); CONFIGURATION OF EXPLOSION TEST DIE (RIGHT), AND OBSERVED FRACTURE PATHS ARE IDENTIFIED IN THE LOWER SECTION BY THE LETTER A AND B. THE EXPLOSIVE WAS DETONATED ON THE T-FRAME SIDE OF THE MODEL. AFTER BABECKI AND PUZAK(36)